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TRANSIENT ELECTRONICS CATEGORIZATION

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Devices for Sensing Branch
Aerospace Components & Subsystems Division

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14. ABSTRACT

Transient electronics is an emerging technology area that lacks proper definitions of what it means to be transient. The purpose of this technical report is to provide a background of the issues related to transient electronic systems and provide a categorization of transience modes to establish a common language for technologists and technology managers. The technical paper can be used as a background document for discussions and internal planning. The scope of this document is limited to the analysis of the technical issues (not solutions) that have influence on the design, fabrication and utilization of transient electronic systems.

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1. EXECUTIVE SUMMARY

Imagine a future where every electronic system has an expiration date and deconstructs itself into harmless and invisible by-products at the end of its lifetime. Apart from providing the manufacturers new business opportunities in replacing such products, the problem of environmental harm caused by the current electronic systems can be eliminated. Further imagine products that not only can deconstruct at pre-arranged dates, but their deconstruction event can be programmed or remotely controlled. Such electronic systems may be regarded as transient electronic systems.

The first question is: why would we want transient electronic systems? Do we want our latest iPhone, for example, to disappear in a year (it is probably obsolete by that time anyway)? Probably not, but compelling arguments exist to make materials in such electronic systems biodegradable to lessen their harm on the environment. Completely vanishing devices will be welcome by everyone when we consider that, for example, over 1.2 billion new cell phones are being manufactured every year.

Electronic waste (e-waste) is one of the fastest growing areas of international waste stream. Initially, the use of miniaturized commercial electronics was considered to be an effective way to reducing resource waste because such products replaced larger and less efficient legacy products. However, miniaturization has led to fast increase in the number of units so that the environmental problems are made worse. It was shown that a reduction by a factor 4.4 in physical mass of electronic devices has increased its use by a factor of 8.[1] The consumer electronics industry in the US accounts for 70% use of the heavy metals, including 40% of lead, found in landfills.[2] IBM expects that within the next 1 to 5 years, about 1 billion people will be using more than a trillion networked objects across the world resulting in an average of 1000 smart products per person in the developed world, each containing a processor and some communication device. Assuming that one smart object has an average mass of 10 g and a service life of one year, there is a minimum 10 kg per person of waste flow per year, for electronics alone.[1] This is already being confirmed by studies in Europe where per capita waste collection of Waste Electrical and Electronic Equipment (WEEE) has reached 6.7kg per person in Ireland and 11 kg per person in Switzerland.[3] The high cost of end-of-lifecycle management of electronic products has prompted the initiation of Design for Environment (DfE) approaches. Although DfE is an important issue for manufacturers, consumers of the products also have key responsibilities along the supply chain. In particular, large governmental organizations, such as the Department of Defense (DoD), can accelerate the implementation of this process.

Transient electronics can be regarded as the ultimate implementation of DfE, where the product end-of-life management is included in the product design. Transient electronics can provide the DoD additional valuable solutions regarding the disposal of fielded devices that are no longer needed. On demand transience features can also be important for protecting the invested

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[1] L. M. Hilty, Electronic Waste – An Emerging Risk?, Environ. Imp. Ass. Rev., 25 (5), p. 431, (2005).
[2] Silicon Valley Toxics Coalition, Fourth Annual Computer Report Card 2003, No. 35.
[3] R. Hischier, R. P. Wager, J. Gauglhofer, Does WEEE Recycling Make Sense from an Environmental Perspective?: The Environmental Impacts of the Swiss Take-Back and Recycling Systems for Waste Electrical and Electronic Equipment (WEEE), Environ. Imp. Ass. Rev, 25 (5), p.525, (. 2005).

intellectual property (IP) in such systems. Because of their inherent complexity, it may not always be possible to field entirely transient DoD electronics that are also environmentally friendly. The protection of IP may be possible by partial transience only, provided that the critical components are transient.

We will examine here technical issues related to transient electronic systems for all applications. Transience is a relatively new feature of electronic systems and its exact meaning is not always clear. The Defense Advanced Research Projects Agency (DARPA) Vanishing Programmable Resources (VAPR) program[4] has the objective of developing "new concepts and capabilities that will enable the transient electronics to become a deployable technology". As the program proceeds, it will become clearer what technology hurdles must be overcome to make this vision a reality. We will only summarize the technical issues as they are known now and categorize them to aid in communications among technologists and managers.

[4] http://www.darpa.mil/Our_Work/MTO/Programs/Vanishing_Programmable_Resources_(VAPR).aspx

2. INTRODUCTION

The idea of building transience into critical electronic systems is not new. Anyone who watched the 1970's television series Mission Impossible is familiar with the self-destruction of the electronic system that delivers the message to the agent. This can be regarded as a programmed transience, but the mode of transience (kinetic) and the remnants (highly visible) make this unsuitable for many applications. In this example, there is little to suggest that transience was a part of the original equipment and, more likely, a kinetic transience mechanism was added later to an ordinary electronic system to make it transient. This is not the intention of true transient electronics, which are designed with transience as a part of their intrinsic design. Nevertheless, the dramatic effect in Mission Impossible makes the point of the desirability of transience of critical systems.

Building transience into electronics will require new thinking. One of the spectacular successes of the electronics industry is the reliability of extremely complex systems. Excellent system level reliability requires that the system components themselves must have projected lifetimes that are measured in centuries. This requirement was met at the fundamental component level (i.e. transistors, diodes) when the transition was made from vacuum tubes to solid state technology in 1950's. Further improvements in manufacturing also produced highly reliable passive circuit components such as capacitors, inductors, interconnectors and transmission lines. The aim of technologists who develop every new generation electronic component has been to make them more durable and not less. The concept of fabricating components with limited lifetimes goes against the current strong technology headwinds.

First, we need to be clear that the transient electronics are not the same as disposable electronics. There are several low cost, high volume consumer applications that require electronics that are embedded within products. Some security and identification tags, single use medical sensors, and large area environmental sensors fall into this category. Although these electronic systems are often manufactured using less durable materials, they are not necessarily easy to recycle. They are only cheap enough to throw away. Therefore, they are not regarded as transient electronics.

Second, we need to overcome the misconception that devices made using organic rather than inorganic materials are inherently transient. This intuitive conclusion is often arrived from our common experience with the organic world that includes plants, animals, food, fuel etc. which are recycled back to nature in relatively short time scales. Therefore, we expect organic based electronics to be less durable and that their transience can be engineered more readily. However, in reality, the man-made organic materials that are suitable for electronic systems are also durable materials whose transience is equally difficult. On the other hand, the defect density, uniformity and the intrinsic electronic properties of organic semiconductors make them less suitable for high performance electronic components (transistors, diodes, capacitors, conductors etc.) in modern electronic systems. Nevertheless, as we will discuss in more detail below, organic materials are becoming a useful part of electronics manufacturing by providing low cost circuit boards and packaging alternatives. Therefore, the transience of electronic components made from both organic and inorganic materials must be considered simultaneously.

Finally, we need to recognize that the electronic systems are very diverse and their manufacture relies on a complex supply chain and very large list of materials, not all of which can be made transient. In general, the larger the system, the more difficult it will be to make it transient. Even when we consider compact and portable electronic systems to make transient, we are faced with a great challenge. As an example consider a common commercial portable electronic system, an iPad. The exploded view of this electronic system shown in Figure 1 reveals the diversity of material used in its construction.[5]

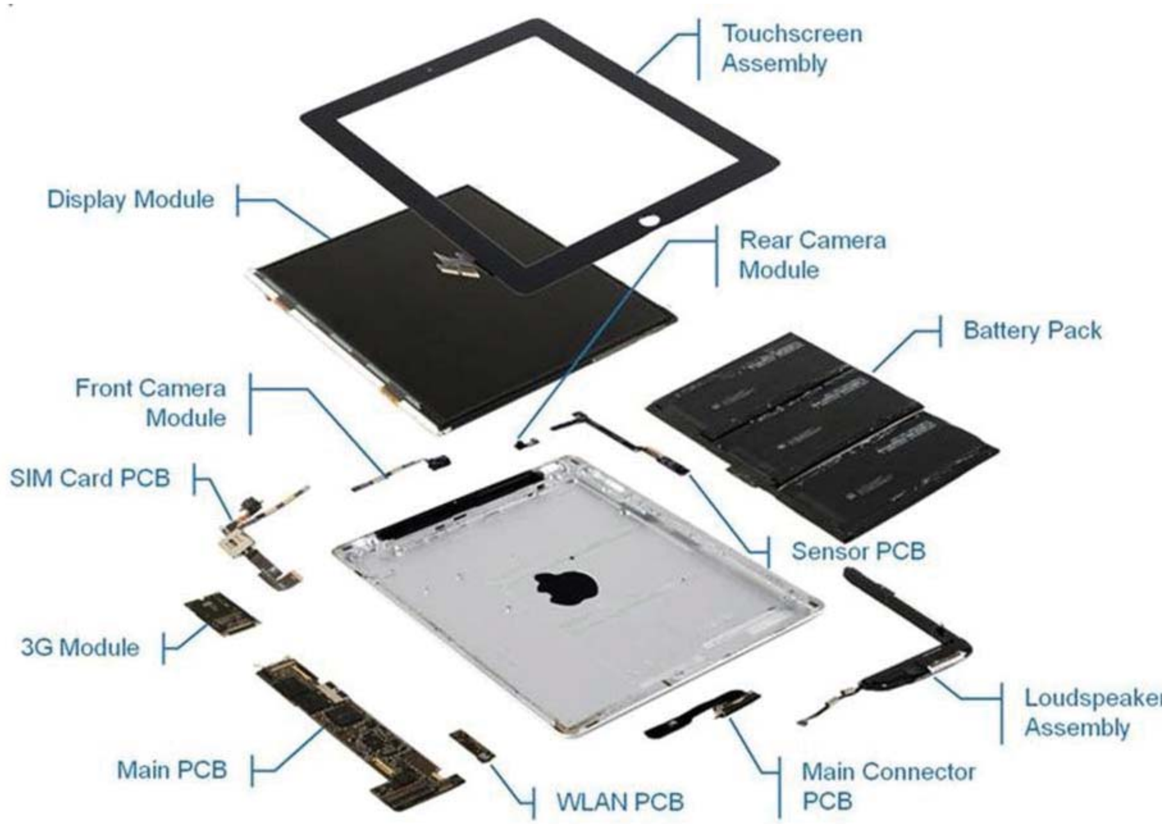

Figure 1: Exploded View of Apple iPad2[5]

The largest components in this product are the battery, the display module, and the case. Whereas the casing material has some flexibility (metal or plastic), the material choices for display and battery are limited by the required performance. For example, the touchscreen needs to be highly conductive and transparent. Currently, only indium-tin oxide (ITO) compounds can meet this requirement. Only a few alternative solutions exist, and none of them are easily made transient. Some of the smaller components contain greater complexity and material diversity. The main circuit board contains several highly integrated circuits for processing, control and memory functions. These circuits are mostly made of silicon. On the other hand, the communication modules (3G and wireless local area network (WLAN)) contain circuits that are made of GaAs. Both circuit boards include a large number of passive components that are made of ceramics. While we need to keep in mind that our aim is to make as much of an electronic system like this as possible be transient, smaller and more compact systems such as networked

[5] http://www.isuppli.com/PublishingImages/Press%20Releases/2011-03-12_iPad2_Exploded.png

sensor modules containing a limited number of components may provide a nearer term application opportunities.

3. TRANSIENT ELECTRONICS CATEGORIZATION

Transient electronics is an emerging technology. When we discuss the transience of a given system, we do not yet have a commonly accepted terminology to specify the type of transience involved. It will be helpful if the most significant transience parameters can be identified and used to define classes of transience to aid such discussions. In this section, we will attempt to identify these parameters and provide preliminary definitions for categories of transience behavior.

Transient Electronics refers to fully functional and complete electronic system that can be made non-functional and physically destroyed on demand or when prearranged conditions are met (programmed). Certain classes of limited lifetime electronics designed to work under harsh environments (e.g. radiation, high temperature, corrosive media etc.), are not regarded to be transient electronics. However, they may be a part of a class of transient electronics with multiple levels of transience, such as slow initial degradation followed by a rapid terminal transience.

Initial Functionality refers to the capability of the transient electronic system prior to the transience event. The performance capability is compared to commercial-off-the-shelf (COTS) non-transient electronic systems. Systems that meet 50-100% of the capabilities of non-transient COTS systems are regarded as fully functional (FF_i). Systems meeting 25-50% of the COTS performances are regarded as partially functional (PF_i). Less than 25% functionality of COTS devices are regarded as limited functionality (LF_i).

Final Functionality refers to the capability of the transient electronics system after the transience event. Completely dysfunctional and inoperative systems are regarded as fully dysfunctional (FD_f), whereas partial functionality (PD_f) is assigned to systems that contain at least one function that is not destroyed by the transience event.

Initial Physical State refers to the physical condition of the transient electronics system prior to the transience event. It is expected that all systems will be in proper physical condition prior to deployment, therefore no values are assigned to this parameter. Multi-level transient electronics may have intermediate physical states between cascaded transience events.

Final Physical State refers to the physical condition of the transient electronic system after the transience event. Systems that are physically converted to remains that are not visible to the naked eye are regarded to have full transience (FT), whereas those systems that are converted to remains that can be observed by the naked eye are regarded to have partial transience (PT). The particle size and dispersion density are contributing factors for the visibility of remains. Particles with any dimension smaller than 1.0mm can be regarded to be invisible to the naked eye. The visibility of end products are also related to their dispersion density. The criteria for particle size and dispersal density will not be considered in this note.

Transience Trigger refers to the mechanisms used to initiate the transience event. Although there may be many types of triggers that can be used for this purpose, we will merge all triggers into 2 groups. The first group includes all on-demand (O) triggers. These types of triggers are remotely controlled. The input signal can be radio frequency (RF), optical, acoustic, mechanical, temperature, or chemical. It requires that the transient electronic system contains at least one receiver that stays in communication with the remote control unit. The second group includes all programmable (P) triggers. These transient electronic systems include trigger components that are pre-programmed to start the transience event. Programming can include timing mechanisms, fusing arrangement, or more complex instructions to respond to pre-determined conditions such as tampering. It can also include specifically engineered transience built into some or all components (programmable transience).

Transience Method refers to the actual mechanism used for the transience. There are many methods of transience and the preferred method will depend on the physical nature of the electronic system. Since most modern electronics contain a variety of component types, as discussed above, a given system may require more than one method of transience. The major transience methods are: dissolution (D), corrosion (C), kinetic (K), scattering (S), and evaporation/ablation (E). Dissolution method relies on the enclosed or the environmentally available chemicals to dissolve the materials in the transient system. The corrosion method relies on oxidation or other means of chemical compositional change to achieve transience. The kinetic method refers to highly energetic means of transience such as explosion. Scattering method causes a breakup of the electronic system and disperses its parts. The evaporation/ablation method converts all or part of the electronic system from a solid to liquid and to a gaseous state. It is likely that a cascade of transience events will be employed for full transience. Therefore, more than one transience method may be used on a given system.

A summary of these transience parameters can be found in Table 1.

Table 1. Summary of Transience Parameters

Initial Functionality	Final Functionality	Final Physical State	Transience Trigger	Transience Method
Fully Functional (FF_i)	Fully Dysfunctional (FD_f)	Full Transience (FT)	On-demand (O)	Dissolution (D)
Partially Functional (PF_i)	Partially Dysfunctional (PD_f)	Partial Transience (PT)	Programmed (P)	Corrosion (C)
Limited Functionality (LF_i)				Kinetic (K)
				Scattering (S)
				Evaporation/Ablation (E)

One method of referring to a transient electronic system is to acknowledge all 5 parameters. For example, a transient system that has 100% COTS performance and becomes fully dysfunctional and invisible to the naked eye after the transient event using mostly dissolution methodologies can be referred as FF_i/FD_f/FT/O/D type of transient system. Although this is a descriptive grouping, it is too long for common use. In addition, when there are multiple methods of transience trigger and transience methods involved, the description becomes unusable. However, such detailed descriptions may be employed to define “Transience Vectors” of future systems in a multi-axis plots.

Initially, a simplification can be provided by concentrating on the most significant parameters. We may assume that the design goals of all transient electronics will be FD_f (fully dysfunctional but not necessarily fully transient). Therefore, only a single value is available and it does not need to be specified. Also, the method of transience need not be specified upfront since more than one may be used. With these simplifications, we can arrive at the following 5 categories of transient electronics.

Table 2. Transient Electronic System Categories

Category	Initial Func.	Final Phys.	Method	Description
A	FF_i	FT	D,C,S,E	Full transience of SOA systems
B	FF_i	PT	D,C,S,E	Partial transience of SOA systems
C	PF_i	FT	D,C,S,E	Full transience of non-SOA systems
D	PF_i	PT	D,C,S,E	Partial transience of non-SOA systems
K	FF_i	PT	K	Partial transience of SOA systems using kinetic methods

In this simplified grouping, a Category A system (Cat A), for example, will have full initial functionality and full transience. The other categories will have similar meanings according to the table. Since the behavior of the Category K system (Cat K) is dominated by the kinetic transience method, this category is mostly defined by that parameter. Kinetic transience refers to highly energetic means of achieving fully dysfunctional end state. Kinetic methods may leave behind visible remains of the original component as well as chemical and physical evidence of transience. It is most likely that a Cat K system will have full initial performance but will not achieve a FT status, and therefore only one type of Cat K transience is defined.

The only parameter that is not involved in this categorization so far is the trigger method. This parameter can be used as a modifier. For example a Cat B system that has on-demand trigger capability can be referred to as Cat B_o system. If both trigger methods are included, it can be referred to as Cat B_{op} system. By this categorization, the stated goal of the DARPA VAPR program is to develop Cat A_{op} transient electronics and the Mission Impossible gadget is a Cat K_p transient electronics system.

This approach can be used to categorize the transience of system components as well as the entire system. For example, in a system that integrates several Si integrated circuits (ICs), a power source, a sensor and a RF antenna on a substrate, we may assign transience categories to each component as well as to the entire system. If, in this example system, the substrate, antenna and the sensor are Cat A, but the Si IC and the power source are Cat B, the entire system will be a Cat B transient system. In very complex and large electronic systems, a Cat B transience may be acceptable provided that some critical components are Cat A. The categorization method described here may be useful as a management tool if a component transience evolves during the development phase.

4. DESIGN FOR TRANSIENCE

As we discussed above, modern electronic systems are very complex and contain a large selection of materials. In principle, most materials that go into such systems can be made transient. One way to accomplish this is to include inside each electronic system mechanisms that will facilitate the deconstruction of each component. These mechanisms may be in the form of chemicals that will dissolve the materials or other mechanisms that will vaporize them. Depending on whether the transient electronic system is designed to be operational for a limited time (disposable) or durable, the inclusion of transience mechanisms may or may not increase the size, weight and cost of the system. Another approach is to construct the entire transient electronic system using new materials that have limited or programmable lifetimes. Ideally, such materials with expiration dates will deconstruct themselves into harmless and invisible remnants. The technology base for such transient electronic components does not yet exist.

Initial examples of transient electronic components technology were recently published.[6] In this example, simple electronic circuits were fabricated on water soluble organic substrates with Mg conductors, as shown in Figure 2. The active component in this case is a Si metal-oxide semiconductor field-effect transistor (MOSFET) with MgO insulators and Mg electrodes. Transience was achieved by immersing the circuit in water, which dissolves the substrate and the conductor lines. The figure shows the condition of the circuit after 5 and 10 minutes of immersion in water. Although the Si chip does not dissolve in water rapidly, it can be made small enough to be undetectable to the naked eye. This is a reasonable example of how transience may be possible with electronic circuits but many questions still remain. Less than ideal electronic materials are used in this example to make them transient. For example, the conductivity of thin film Mg is a third of copper, which makes it unsuitable for high speed digital and microwave circuits.

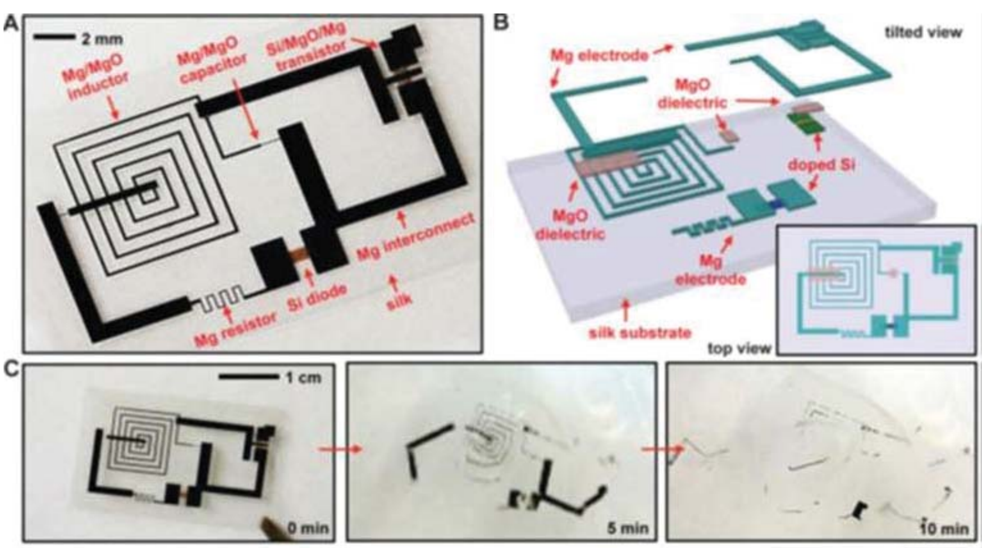

Figure 2: Initial Examples of Transient Electronic Circuits[6]

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[6] Suk-Won Hwang *et. al.*, "*A Physically Transient Form of Silicon Electronics"*, Science 337, 1640 (2012).

In the example discussed above, all circuit components were designed to be transient in the same fashion (i.e. soluble in water). One transience method may not be sufficient for other components that are not discussed here. In designing transient electronic systems, therefore, the transience of 3 major system components must be considered. These are: 1) Active Devices and Passive Components, 2) Integration Substrate, 3) Packaging.

Active devices and passive components are the brains of any electronic system. They are the fundamental building blocks and their performance is critically related to the overall system performance. In modern systems, both the active (transistors, diodes, micro-electromechanical systems (MEMS)) and the passive components (capacitors, inductors, interconnects, transmission lines) are integrated on small semiconductor substrates. It is no longer meaningful to achieve any kind of acceptable electronic performance from non-integrated circuits; therefore any transience solution has to deal with the entire integrated circuit, and not with individual components.

Integration substrates are the boards on which various integrated circuits and other system functions are integrated. Sometimes these are called circuit boards or panels. These substrates can be used to route signals between various sub-systems. Substrates can provide an integration platform for a variety of components, not all of which are necessarily highly integrated. Some components can be physically attached to the substrate and electrical connections are made using wire bonding or other more conventional techniques. The integration of optical, acoustic, magnetic or other types of components may require more specialized hybrid integration approaches. The communication between substrates can be accomplished using electrical connectors ribbons or optical fibers.

Packaging is the final protective cover for the electronic system. By definition, it is designed to be durable against environmental elements such as moisture, temperature, mechanical stress, and corrosion.

While it is clear that all parts of the electronic system design must be examined and re-engineered for transience, the miniaturization of the whole system goes a long way toward making the final product transient. Approaches such as system-in-package (SiP) [7], 3D-integration[8,9] and system-on-chip (SoC)[10] that are already being pursued for other reasons can be beneficial towards designing transient systems.

An example of the SiP technology approach is illustrated Figure 3. Multiple ICs are closely packed inside a common package that includes a mini substrate which routes signals between chips. An even higher level of integration is possible if the actual Si IC chips are mounted

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[7] http://cache.freescale.com/files/shared/doc/reports_presentations/RCPPRESENTATION.pdf
[8] http://en.wikipedia.org/wiki/Three-dimensional_integrated_circuit
[9]http://www.darpa.mil/Our_Work/MTO/Programs/DAHI/Diverse_Accessible_Heterogeneous_Integration_(DAHI).aspx
[10] http://en.wikipedia.org/wiki/System_on_a_chip

directly on the substrate without a need for individual packaging.[11,12,13] An illustration of this technology,[14] which is sometimes referred to as *"die embedded packaging"* is shown in Figure 4. While the main emphasis of these technology thrusts is the compactness of systems for performance and lower cost, the same technology approaches can be useful for transient electronic systems by minimizing the total material content. This advantage must be balanced against the need to physically access various integrated components during the transience event. Since a range of materials are closely compacted in a small volume, the transience method(s) used for the outer layers may interfere with other transience methods needed for inner components.

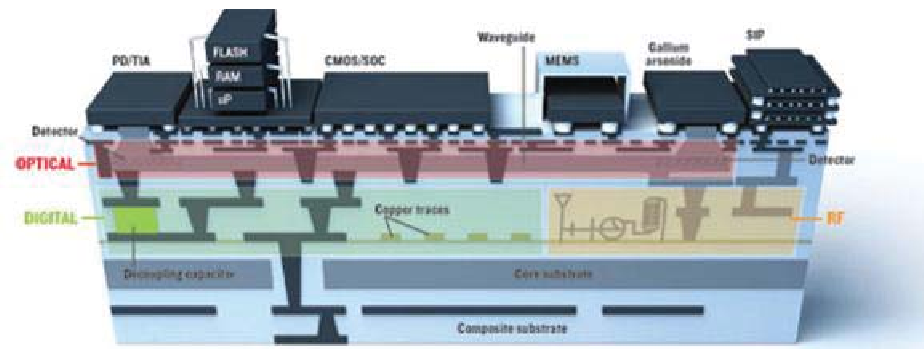

Figure 3: Illustration of SiP Integration Technology[7]

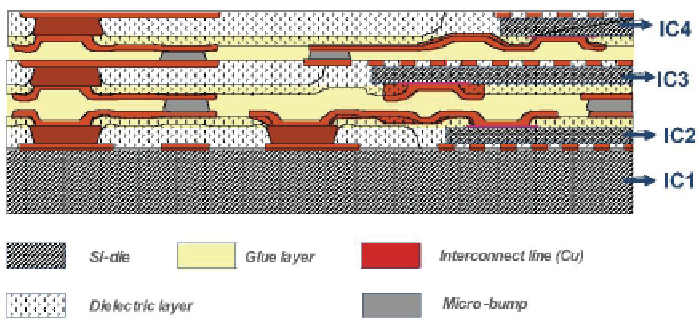

Figure 4: In Die-Embedded Circuits, Unpackaged (naked) IC Die is Directly Integrated Inside Substrates[14]

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[11] L. Boettcher , D. Manessis , A. Ostmann , S. Karaszkiewicz and H. Reichl "*Embedding of chips for system in package realization—Technology and applications*", 3rd Int. Microsyst., Packag., Assembly, Circuits Technol. Conf. (IMPACT), pp.383 -386 (2008).
[12] E. Jung , A. Neumann , D. Wojakowski , A. Ostmann , R. Aschenbrenner and H. Reichl "Ultra thin chips for miniaturized products", Proc. IEEE Electron. Components Technol. Conf. (ECTC), pp.1110 -1113 (2002).
[13] J. N. Burghartz , W. Appel , C. Harendt , H. Rempp , H. Richter and M. Zimmermann "*Ultra-thin chip technology and applications, a new paradigm in silicon technology*", Solid-State Electron., vol. 54, pp.818 -829 2010.
[14] E. Beyne, "3D System Integration Technologies," in *2006 International Symposium on VLSI Technology, Systems, and Applications*, 2006, pp. 1-9.

5. ORGANIC VS. INORGANIC

Both organic and inorganic materials are used in the manufacture of modern electronic systems. At the dawn of the electronics age, nearly 100 years ago, nearly all parts of the electronic devices were made from inorganic materials. There were two good reasons for that approach. First, early electronic devices were vacuum tube based and required the use of high temperature metal and glass. Second, there were limited choices in organic materials before plastics were introduced. The only significant use of organic materials was in the production of casings. Initially wood was used but later synthetic organics such as Bakelite was introduced for this purpose.[15] Today, organic materials make up a significant portion of electronic products, but their use is still concentrated around the tail end of manufacturing value chain. The most significant parts of modern electronics systems are still implemented using inorganic semiconductors, high conductivity metals and inorganic insulators. As shown schematically in Figure 5, as we move away from highly integrated circuits at the heart of electronics towards final protective packaging, organic material content becomes significant. The trend is toward higher organic materials content in electronic systems, as indicated by the broken line in Figure 5. Packaging and circuit boards are increasingly made of organic substances. Some specialized (hermetically sealed) packages and microwave circuit boards may continue using inorganic materials in the future. The organic content of active and passive devices, integrated ICs, interconnects will likely continue to be made of inorganics to maintain performance and complexity. Power sources and antennas will likely have both organic and inorganic components.

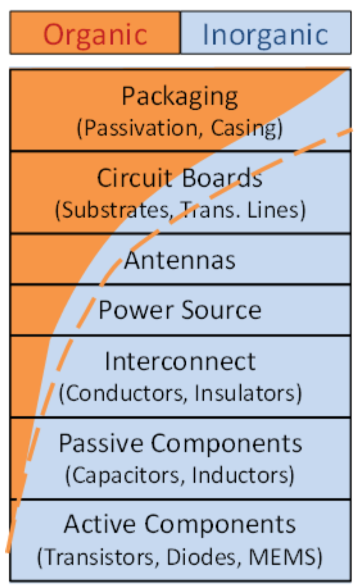

Figure 5: Material Content of Electronic System Technology Components
The organic material content of technology components tend to increase toward the final stages of manufacturing. The broken lines indicate future trends.

[15] http://en.wikipedia.org/wiki/Bakelite

6. TRANSIENCE ISSUES

In this section, we will review the top-level issues involved in the transience of electronic systems. It is tempting to think that a single method of transience can be used if all the materials for all components of a system can be made compatible with that method. Apart from Cat K transience methods, such a unified solution does not exist today. We will analyze transience requirements by examining the materials choices that are available for various technology components of an electronic system as indicated in Figure 5.

Active Components are at the heart of every electronic system. Without them, the system would not be called "electronic". Over the years, such components have been miniaturized and integrated together on a single chip of a semiconductor substrate. The modern microprocessors and memory chips contains billions of active components. Intrinsically it is possible to create transient versions of these components by, for example, introducing defects in semiconductor crystals which causes a failure of the component after a time period. Alternatively, a new class of devices, which are less durable, can be developed to replace the current ones. Thus, for example, some metal-oxide thin film transistors (e.g. nanocrystalline ZnO) are highly soluble in water with pH <5. Both of these approaches, however, have limitations in device performance and integration complexity and will not directly replace the current active devices in integrated circuits. The best that can be expected with systems made entirely with new classes of active devices will be Cat B transience in the near term.

The majority of active components in non-transient electronic systems are made of Si. With the exception of power electronics, where high voltage devices are involved, Si-based devices are highly integrated. Other semiconductors used in RF systems include III-V compound semiconductors such as GaAs and InP as well as II-VI compound semiconductors such as GaN. New carbon-based inorganic electronic devices are also being developed but they are not yet used in real systems. In semiconductor manufacturing, various wet and dry chemical processes are used to remove potions of semiconductors and other parts of the active devices (e.g. electrodes, insulators). These established chemistries can form the basis of transience of completed devices. A list of chemistries involved is illustrated in Table 3.[16]

[16] http://en.wikipedia.org/wiki/Etching_(microfabrication)

Table 3. Etchants for Common Microfabrication Materials [16]

Material to be etched	Wet etchants	Plasma etchants
Aluminium (Al)	80% phosphoric acid (H_3PO_4) + 5% acetic acid + 5% nitric acid (HNO_3) + 10% water (H_2O) at 35–45 °C[3]	Cl_2, CCl_4, $SiCl_4$, BCl_3[4]
Indium tin oxide [ITO] (In_2O_3:SnO_2)	Hydrochloric acid (HCl) + nitric acid (HNO_3) + water (H_2O) (1:0.1:1) at 40 °C[5]	
Chromium (Cr)	• "Chrome etch": ceric ammonium nitrate ($(NH_4)_2Ce(NO_3)_6$) + nitric acid (HNO_3)[6] • Hydrochloric acid (HCl)[6]	
Gallium Arsenide (GaAs)	• Hydrochloric Acid (HCl) • Citric Acid diluted ($C_6H_8O_7$: H_2O, 1 : 1) + Hydrogen Peroxide (H_2O_2)+ Water (H_2O)	Cl_2, CCl_4, $SiCl_4$, BCl_3, CCl_2F_2
Gold (Au)	Aqua regia, Iodine and Potassium Iodide solution	
Molybdenum (Mo)		CF_4[4]
Organic residues and photoresist	Piranha etch: sulfuric acid (H_2SO_4) + hydrogen peroxide (H_2O_2)	O_2 (ashing)
Platinum (Pt)	Aqua regia	
Silicon (Si)	• Nitric acid (HNO_3) + hydrofluoric acid (HF)[3] • Potassium hydroxide (KOH) • Ethylenediamine pyrocatechol (EDP) • Tetramethylammonium hydroxide (TMAH)	CF_4, SF_6, NF_3[4] Cl_2, CCl_2F_2[4]
Silicon dioxide (SiO_2)	• Hydrofluoric acid (HF)[3] • Buffered oxide etch [BOE]: ammonium fluoride (NH_4F) and hydrofluoric acid (HF)[3]	CF_4, SF_6, NF_3[4]
Silicon nitride (Si_3N_4)	• 85% Phosphoric acid (H_3PO_4) at 180 °C[3] (Requires SiO_2 etch mask)	CF_4, SF_6, NF_3,[4] CHF_3
Tantalum (Ta)		CF_4[4]
Titanium (Ti)	Hydrofluoric acid (HF)[3]	BCl_3[7]
Titanium nitride (TiN)	• Nitric acid (HNO_3) + hydrofluoric acid (HF) • SC1 • Buffered HF (bHF)	
Tungsten (W)	• Nitric acid (HNO_3) + hydrofluoric acid (HF) • Hydrogen Peroxide (H_2O_2)	CF_4[4] SF_6[citation needed]

This is not an exhaustive list and does not contain all materials involved in active device manufacture and methods of dissolving them. Plasma etchants require ionized reactive agents to start the chemical reaction. This is accomplished in vacuum plasma reactors in manufacturing. Such methods may be difficult to implement as transience methods. Chemical reactions often require elevated temperatures and strong acids or alkaline solutions, which must be considered in developing transience methods. The other consideration is that a significantly large etchant-to-material volume ratio of is often required for these processes. An etchant/material volume ratio of 10:1 to 100:1 is not unusual. Another commonly used, but not included in this table, etchant for Si substrates is XeF_2.[17,18] The advantage of this etchant is that it is a dry compound and a relatively low volume ratio is needed for etching.

The actual etch rate of electronic materials listed in Table 3 depend on many factors including temperature, crystal orientation, doping level as well as the etch chemistry. Initially, only slower etch (~0.1μm/min) chemistries were developed for the electronic industry for precise removal of thin layers. Recently, however, MEMS manufacturing has extended this field to faster etch rates (>10μm/min).[19] An extensive tabulation of etch rates for various electronic materials can be found in the Appendix.[20]

Passive Components are essential to the operation of the electronic circuits. Since they are strictly linear devices, they can be made of non-semiconductor materials such as insulators and conductors. They are mostly used in close proximity to the active components in integrated circuits. Therefore, their construction materials are similar to those used in active devices and they are made mostly of inorganic materials. Specialized versions of passive components are found in circuit boards outside the integrated circuit chips. These "discrete" passive components, capacitors, inductors, and resistors, play a significant role in achieving the overall performance of the electronic systems. In some cases, they are large storage capacitors to temporarily store energy for pulsed operation. In other cases, they are high-Q inductors for temporarily storing high RF energy during every cycle. Such external passive components can be a significant material content of a modern RF electronic system. A cell phone circuit board example in Figure 6 illustrates the dominance of passive components in RF circuit boards.[21] Advanced integration methods, such as "*die embedded technology*" described above, can help in reducing the material content of passive components for easier transience.

[17] http://www-bsac.eecs.berkeley.edu/projects/ee245/Lectures/lecturepdfs/Lecture2.BulkMicromachining.pdf
[18] https://www.mems-exchange.org/MEMS/fabrication.html
[19] M. J. Madou, "MEMS fabrication", in The MEMS Handbook, CRC Press, New York, NY, Ch. 16, pp1-183, (2002).
[20] K. R. Williams, K. Gupta, and M. Wasilik, "Etch Rates for Micromachining Processing—Part II", J. Microelectromechanical Sys., vol. 12, pp.761-778, (2003).
[21] http://www.gigacircuits.com/technology.html

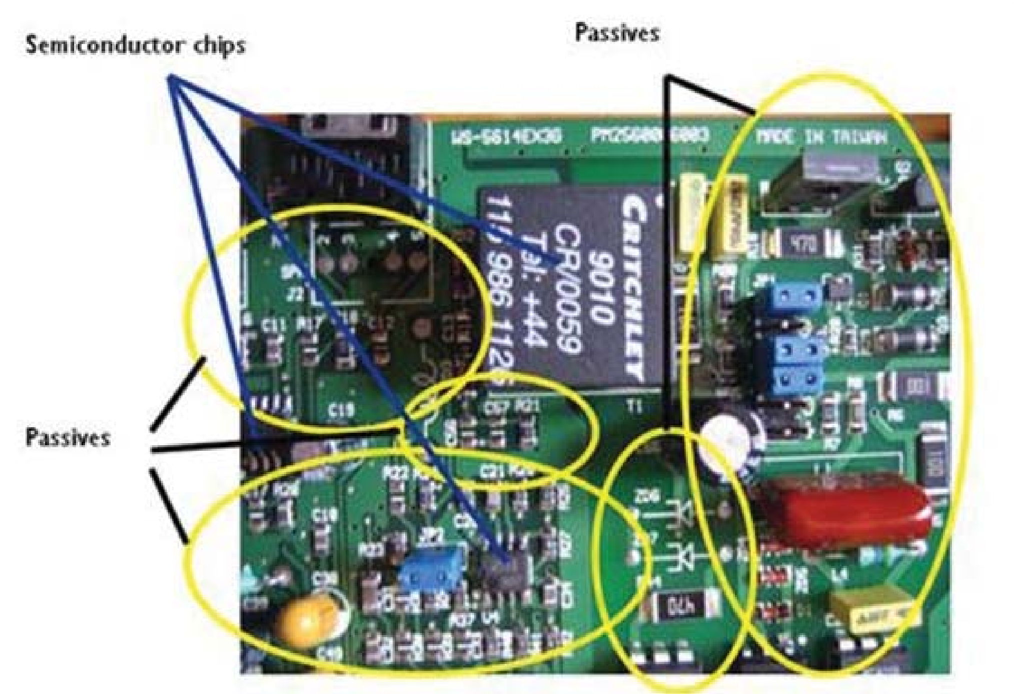

Figure 6: Section of a Cell Phone Circuit Board Showing Extensive use of Passive Components[21]

Interconnects are connections and isolation between various active and passive components as well as the antenna. They are also used in power and signal distribution. Although conductors are almost exclusively made of metals, and therefore are inorganic, some insulators can be made of organic materials. On a circuit board (substrate), conductors are separated by air or the substrate. Their transience can be managed since they are readily accessible from outside. Interconnects inside an integrated circuit are mostly inorganic and highly miniaturized,[22] as shown in Figure 7. Their transience must be managed together with active and passive components.

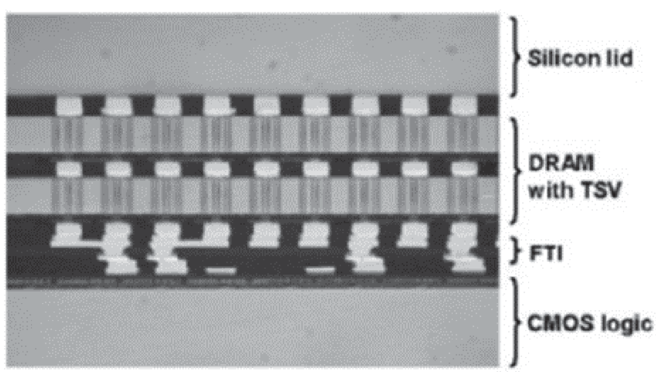

Figure 7: Cross-section of a Si IC Showing Layers for Active and Passive Components as well as Interconnects[22]

[22] Y. Kurita, S. Matsui, N. Takahashi, K. Soejima, M. Komuro, M. Itou, *et al.*, "A 3D Stacked Memory Integrated on a Logic Device Using SMAFTI Technology," in *2007 Proceedings 57th Electronic Components and Technology Conference*, 2007, pp. 821-829.

Power Sources usually refer to batteries in portable electronic systems. There are many types of batteries that are in use today in commercial and military electronics. They can make up a significant portion of the electronic system, as shown in Figure 1. Therefore, their transience is very important. There is a significant interest and effort to make batteries in commercial systems transient (at least recyclable) for environmental protection. The use of organic or inorganic materials in their construction is not currently a significant factor in their transience. Other types of power sources that can be used in small electronic systems are the energy harvesters.[23] Solar cells are the most common energy harvesters. Their construction is similar to semiconductor active devices and therefore their transience solution will also be similar. RF energy harvesters find use in low power sensor applications.[24] They have simpler construction and their transience characteristics have been reported. [25]

Antennas are needed for communication and sensor systems for transmitting or receiving RF signals. Within the context of transient electronic systems, we are mostly interested in integrated antennas which have a lot common in their fabrication with interconnects discussed above. We can assume similar material content for these components as interconnects. In trying to make them integrated with the rest of the system and to minimize their sizes for easier transience, however, we come across physical limitations. Antennas are the interface between the physical space and the electronics for signal transmission. Since they need access to the space outside the electronic system, they are mostly placed on the outside of the package, which may introduce challenges for embedded transience mechanisms to reach them. Also, the size of antennas is closely related to the signal frequency due to the fact that they are essentially resonant structures and their size cannot be arbitrarily reduced. The use of high dielectric constant dielectrics[26] can help to reduce the size of antenna at the expense of introducing new materials (high temperature ceramics) with challenging transience requirements.

Circuit Boards are the substrates on which various electronic compounds are integrated. In a typical circuit board shown in Figure 6, multiple integrated circuits and passive components are integrated. Depending on the application, a circuit board may contain organic and inorganic materials and can be rigid or flexible. In complex systems, circuit boards contain multiple layers to accommodate interconnection between components.

We can group circuit boards into 5 categories. 1) **Metal**: These are used for power electronics and the main purpose is to provide good heat sinks. 2) **RF:** These are made of low dielectric constant plastics, ceramics or quartz. The mechanical properties are less important in this application than electrical properties. In microwave applications, a circuit board may support transmission lines and provide thermal heat sinking paths. At lower microwave frequencies, a combination of organic and inorganic substrates can be used. 3) **FR-4:** These are made from woven fiber glass materials which have been supported by high temperature plastics. These substrates are rigid and can be processed in large sheets. 4) **FR-2:** These specialized paper

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[23] Eric M. Yeatman, "*Energy harvesting – small scale energy production from ambient sources*", Proc. SPIE 7288, Active and Passive Smart Structures and Integrated Systems 2009, 728802 (April 06, 2009); doi:10.1117/12.824472
[24] Mathúna CO, O'Donnell T, Martinez-Catala RV, Rohan J, O'Flynn B. "*Energy scavenging for long-term deployable wireless sensor networks*", Talanta, 2008 May 15; 75(3):613-23.
[25] Dagdeviren C, Hwang SW, Su Y, Kim S, Cheng H, Gur O, Haney R, Omenetto FG, Huang Y, Rogers JA, "*Transient, Biocompatible Electronics and Energy Harvesters Based on ZnO*", Small, 2013 Apr 19.
[26] http://www.roundsolutions.com/shop/products/en/Antennas/Ultra-Small-Embedded-Ceramic-GPS-Antenna.html

products and are used in lower cost applications. 5) **FLEX:** The main feature of these substrates is that they are flexible and thin. Polyimide, which is a high temperature plastic, is the main material choice for this application. Naturally, the appropriate transience method for each type of circuit board type will be different. The current materials used for this technology component are highly stable and difficult to make transient. Therefore, new substrate materials may need to be developed for transient electronics applications.

Packaging is the protective layer around the electronic system. Depending on the size, shape and the application of the system, packaging can vary from a simple plastic molding layer to a more durable metal package. The appropriate transience method for packaging will therefore strongly depend on the actual material properties. Assuming that effort has been made in designing electronic systems for transience and maximum compactness has been achieved through for example SiP or die-embedded technologies (discussed above), the packaging material can be a plastic whose transience can also be managed. De-polymerization is a useful approach to convert solid content (polymer) to vapor (monomer) at relatively low temperatures.[27]

[27] http://en.wikipedia.org/wiki/Thermal_depolymerization

7. TRANSIENCE VECTOR

Transience categorization may help us to define future directions in transient electronics evolution. Based on the definition of transience categories above (e.g. see Table 2), a 2-D representation of transience categorization can be made on a Transience-Initial Functionality space. As shown in Figure 9, the entire available space is not covered with the available categories. Low transience and limited initial functionality sections of the available space are not used. The remaining space is divided among Cat A-D according to their definition. Cat K is a special case with much narrower foot print in this space.

Cat A is currently the goal of the VAPR program, but Cat B may also be acceptable for many applications provided that critical components are made transient. Cat C and Cat D may have limited acceptance due to lower functionality of products. However, all categories may have eventual applications and they will be all considered within the context of technology vector definition. Examples of the type of applications that may be considered for each category are shown in Figure 9.

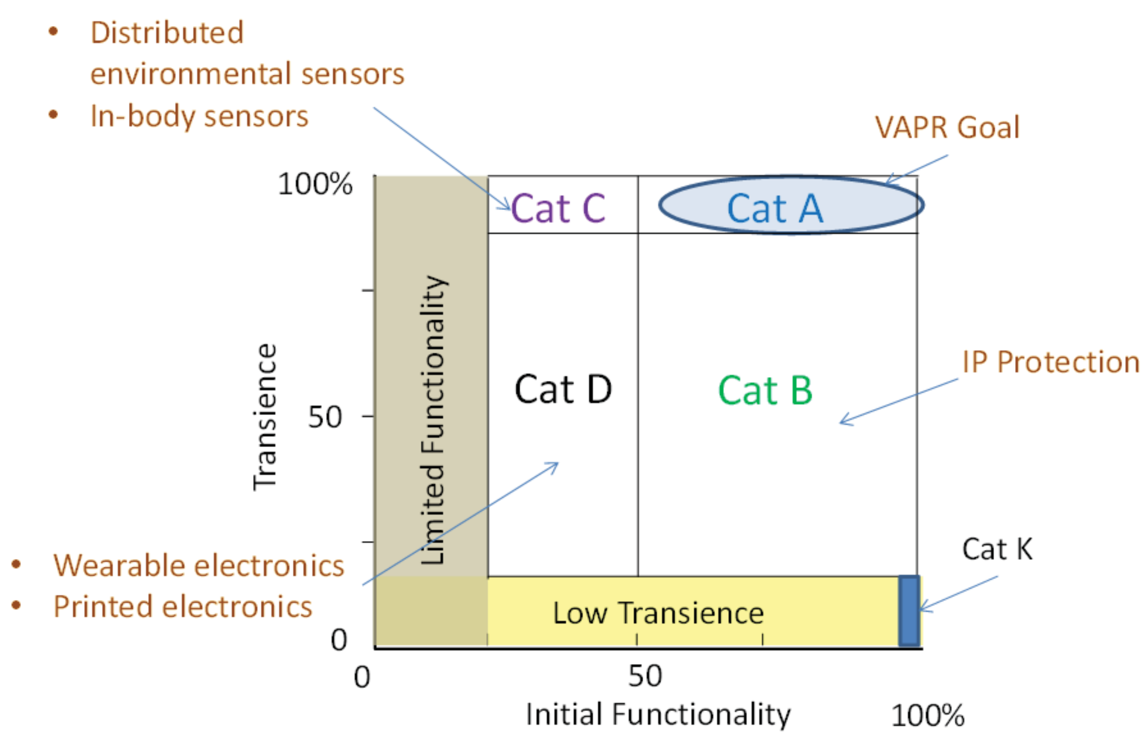

Figure 8: Mapping of Transience Categories on Transience-Initial Functionality Space

Building on the mapping structure of Figure 9, we can expand the transience space into 3-D by adding a "product complexity" dimension, as shown in Figure 10. The product complexity can be defined in different ways depending on specific applications. In this example, the electronic product is assumed to be a complete system which is composed of sub-systems, panels (boards) and a variety of lower level components such as circuits. Each circuit may also contain active and passive components, but they are not shown in this figure. Cat A component transience in a complex product may result in an overall Cat B transience of the entire product. Cat K transience can be assumed to be independent of product complexity since it always results in low transience. Cat A and Cat B transience will tend toward Cat B and Cat C transience, respectively as the complexity is increased. One measurable metric in transient electronic system development may be the crossover point from Cat A to Cat B (also from Cat C to Cat D). The push of transient electronics technology should be to increase this cross-over point to highest complexity. Full success of this thrust will result in environmentally safe and fully transient complex products, as indicated by the top red arrow in Figure 10 .

Cat B may be acceptable for some DoD applications provided that critical components are made transient. Similarly, pushing the Cat A-Cat B transition point toward higher product complexity will yield higher levels of IP protection.

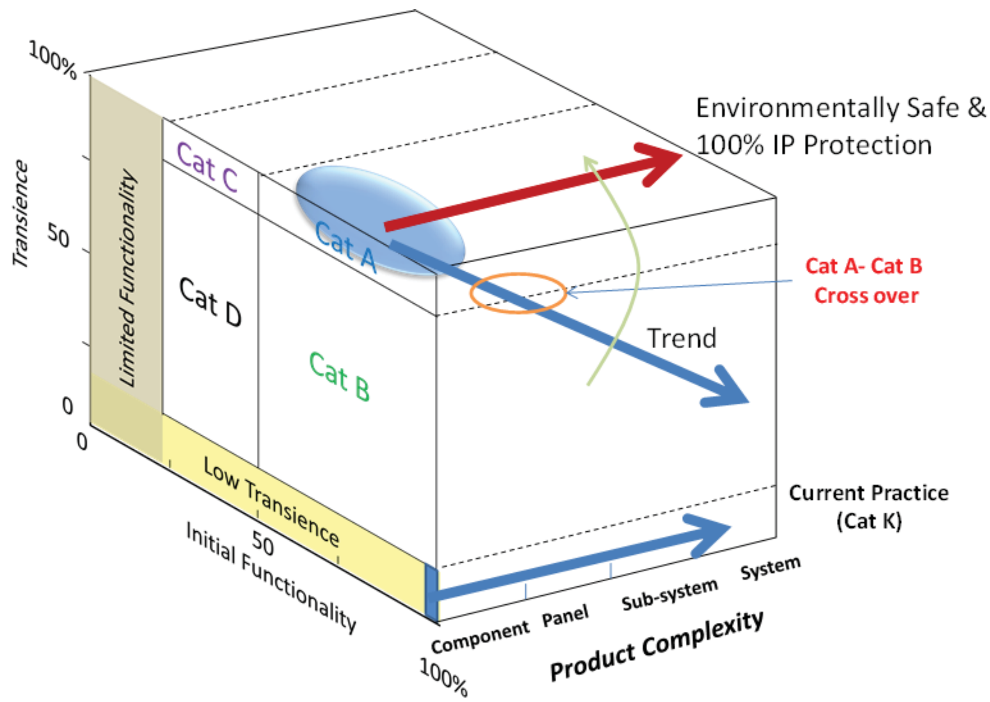

Figure 9: Transience Categories Mapped on 3-D space of Transience-Initial Functionality-Product Complexity

8. SUMMARY

We have provided a top-level look at the prospects and the challenges of transient electronics technology. This is an emerging technology area that provides valuable application opportunities for both DoD and for environmental protection. An electronic system that deconstructs itself at the termination of its mission is a valuable asset for the DoD for the protection of the IP contained in the system. Similar systems are preferred for consumer applications to minimize the environmental impact. However, transient electronics technology does not exist today. In fact, all components of an electronic system are developed with the maximization of its durability and reliability in mind. A new development paradigm is therefore needed to manage this emerging technology.

This report provides an analysis of the electronic system technology components and highlights the issues related to increasing their transience. The overall preferred approach is to develop transient version of each technology component and build the electronic system using these technologies. This approach is more feasible for back end technologies such as substrates and packaging. More highly integrated and complex technologies related to active and passive components are more difficult to make transient. Fortunately, the volume and size of such components are relatively small, and initially their transience may need to be facilitated as a part of the transience of larger compounds. It is clear that a single transience method will not be suitable for all technology components and multiple methods may need to be used in parallel or in sequence.

We also provided relevant definitions of technology components and a categorization of transience to aid in communication among those involved in technology development and management. Technical approaches of the current VAPR program performers are mapped onto transience-initial functionality-product complexity space to aid in technology development management.

APPENDIX: ETCH RATES FOR COMMON ELECTRONIC MATERIALS

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Etch Rates for Micromachining Processing—Part II

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***Abstract*—Samples of 53 materials that are used or potentially can be used or in the fabrication of microelectromechanical systems and integrated circuits were prepared: single-crystal silicon with two doping levels, polycrystalline silicon with two doping levels, polycrystalline germanium, polycrystalline SiGe, graphite, fused quartz, Pyrex 7740, nine other preparations of silicon dioxide, four preparations of silicon nitride, sapphire, two preparations of aluminum oxide, aluminum, Al/2%Si, titanium, vanadium, niobium, two preparations of tantalum, two preparations of chromium, Cr on Au, molybdenum, tungsten, nickel, palladium, platinum, copper, silver, gold, 10 Ti/90 W, 80 Ni/20 Cr, TiN, four types of photoresist, resist pen, Parylene-C, and spin-on polyimide. Selected samples were etched in 35 different etches: isotropic silicon etchant, potassium hydroxide, 10:1 HF, 5:1 BHF, Pad Etch 4, hot phosphoric acid, Aluminum Etchant Type A, titanium wet etchant, CR-7 chromium etchant, CR-14 chromium etchant, molybdenum etchant, warm hydrogen peroxide, Copper Etchant Type CE-200, Copper Etchant APS 100, dilute aqua regia, AU-5 gold etchant, Nichrome Etchant TFN, hot sulfuric+phosphoric acids, Piranha, Microstrip 2001, acetone, methanol, isopropanol, xenon difluoride, $HF+H_2O$ vapor, oxygen plasma, two deep reactive ion etch recipes with two different types of wafer clamping, SF_6 plasma, SF_6+O_2 plasma, CF_4 plasma, CF_4+O_2 plasma, and argon ion milling. The etch rates of 620 combinations of these were measured. The etch rates of thermal oxide in different dilutions of HF and BHF are also reported. Sample preparation and information about the etches is given. [1070]**

***Index Terms*—Chemical vapor deposition (CVD), etching, evaporation, fabrication, materials processing, micromachining.**

I. Introduction

WHEN designing a microfabrication process, the etch rate of each material to be etched must be known. Knowing the etch rates of other materials that will be exposed to the etch, such as masking films and underlying layers, enables an etch process to be chosen for good selectivity (high ratio of etch rate of the target material to etch rate of the other material)—if one exists. While several large literature-review compilations of etches that target specific materials have been made [1], [2], these only report etch rates in some cases, and rarely have corresponding selectivity information. This paper provides such information, expanding on an earlier paper [3] to give 620 etch rates of 53 materials in 35 etches that have been used or may be used in future fabrication of microelectromechanical systems (MEMS) and integrated circuits (ICs) (approximately 50 etch rates measured in the earlier paper have been included in this one). These data allow the selection of new combinations of structural material, underlying material, and etchant for micromachining.

Table I summarizes the etches tested, abbreviated names for the etches, and the target materials for each. Table II lists etch rates of Si,Ge, SiGe, and C in the SI units of nm/min (not Å/min as in the earlier tables) [3]. Table III covers films and wafers that are primarily silicon dioxide, produced under many different conditions. Table IV is on silicon nitride and aluminum oxide. Table V covers the metals Al, Ti, V, Nb, Ta, and Cr. Table VI continues with the metals Mo, W, Ni, Pd, Pt, Cu, Ag, Au, alloys 10 Ti/90 W, 80 Ni/20 Cr, and compound TiN. Finally, Table VII gives etch rates of organics: photoresists, a resist pen, and a spin-on polyimide.

Section II of this paper lists the materials etched, their preparation, and some uses or potential uses in MEMS and ICs. Section III describes the preparation and applications of the wet and dry etches that were studied, as well as some key experimental results. Section IV describes etch-rate measurement techniques, and Section V discusses the results.

II. Sample Preparation

The preparation of the samples in the etch-rate tables is described below, listed by the labels (in italics) used across the tops of the tables. All coated materials were deposited on 100-mm-diameter silicon wafers. For the isotropic silicon etchant, potassium hydroxide, and a few other etches, the wafers were first coated with LPCVD silicon nitride so that etches would not penetrate into the silicon or attack the back side of the wafer.

In several cases, similar materials were prepared using different methods (e.g., wafer form, PECVD, LPCVD, and ion-milled silicon dioxide; annealed and unannealed films) to study and emphasize the effect on their etching characteristics.

Existing or potential MEMS applications are given for the materials. Many of the materials were discussed in more detail previously [3].

A. Silicon, Germanium, SiGe, and Carbon

(100) Si Low-Doped Wafer: Single-crystal silicon, (100) orientation, phosphorus-doped n-type, resistivity of 3–40 Ω-cm, grown with the Czochralski (CZ method). Single-crystal silicon is the standard starting material for bulk micromachining.

Float-Zone Si Wafer: Single-crystal silicon, (100) orientation, undoped, grown with the float-zone (FZ) method for a high resistivity of >10 000 Ω-cm. Float-zone wafers have been used as substrates in RF MEMS application to reduce eddy-current loss.

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LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

ACRONYM	DESCRIPTION
AFRL	Air Force Research Laboratory
C	corrosion
COTS	commercial-off-the-shelf
D	dissolution
DARPA	Defense Advanced Research Projects Agency
DfE	Design for Environment
DoD	Department of Defense
E	evaporation/ablation
e-waste	electronic waste
FD_f	fully dysfunctional
FF_i	fully functional
FT	full transience
IC	integrated circuit
IP	intellectual property
ITO	indium-tin oxide
K	kinetic
LF_i	limited functionality
MEMS	micro-electromechanical systems
MOSFET	metal-oxide semiconductor field-effect transistor
O	on-demand
P	programmable
PD_f	partially dysfunctional
PF_i	partially functional
PT	partial transience
RF	radio frequency
S	scattering
SiP	system-in-package
SoC	system-on-chip
VAPR	Vanishing Programmable Resources
WEEE	Waste Electrical and Electronic Equipment
WLAN	wireless local area network